Clarkson
UNIVERSITY

WALLACE H. COULTER SCHOOL OF ENGINEERING
Technology Serving Humanity

MEMORANDUM

Subject: Progress Report
ULI: FY13 Q4 Progress Report (7/1/2013–9/30/2013)

This document provides a progress report on the project "Advanced Digital Signal Processing" covering the period of 7/1/2013–9/30/2013.

20150309473

William D. Jemison, Professor and Chair, PO Box 5720, Clarkson University, Potsdam, NY 13699-5720
315-268-6509, Fax 315-268-7600, wjemison@clarkson.edu

Award Information

Award Number	N000141110371
Title of Research	Advanced Digital Signal Processing for Hybrid Lidar
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The technical objective of this project is the development and evaluation of various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance. Practical algorithms must be developed taking into account the underwater propagation channel and the processing requirements for each algorithm as shown in Figure 1.

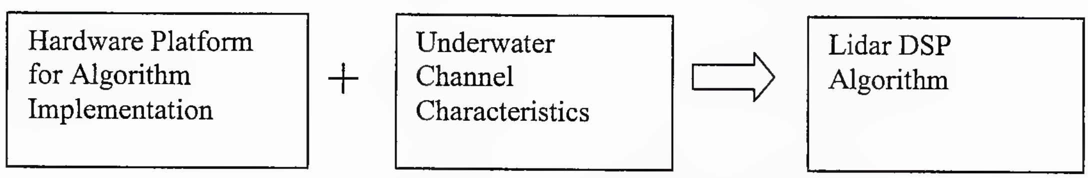


Figure 1. The development of lidar DSP algorithms must take into account hardware implementation and underwater channel characteristics.

Technical Approach

A significant challenge in hybrid lidar-radar is optical absorption and scattering. The absorption of the light photons by the molecules in the water channel contributes to a decrease in the total signal level collected at the receiver. This unwanted phenomenon can be reduced by selecting the wavelength of the laser light to be in the blue-green region. Backscattering occurs when transmitted light signal reflects off a water particulate and reaches the detector without first reaching the object. Thus, backscattered light contains no information regarding the object and it reduces the image contrast and resolution as well as the object ranging measurement accuracy. There have been various methods that attempt to reduce the backscatter. One method is to increase the modulation frequency beyond 100MHz and another is to use a dual high-frequency (>100MHz) approach that uses high speed modulation to help suppress backscatter while also providing an unambiguous range measurement. In general, it is desired to determine which combination of Radio Frequency (RF) modulation frequencies, modulation waveforms, and signal processing algorithms help improve hybrid lidar-radar performance in a variety of underwater environments.

The approach is to focus on the optical proximity detector that is being developed with ONR funding. The goal is to replace analog hardware with digital components to benefit from the advantages offered with digital hardware and signal processing, including better sensitivity due to large dynamic range digitizers and lossless digital demodulation and filtering, reconfigurability via software to improve sensor adaptability in different environments and for multiple applications, and real-time processing for instant feedback.

Progress Statement Summary

In FY12 we developed a new backscatter reduction technique that leverages spatial filtering techniques used in through the wall imaging (TTWI) radar. The technique was validated using both simulated and experimental data. Simulated data was generated using Rangefinder, a lidar simulation tool developed by the Navy. This data was then processed using the spatial filter and ranging performance between the filtered and unfiltered data were compared. In addition, experimental ranging data taken in a Navy test tank were also used to validate the filter and ranging measurement results with and without the application of the spatial filter in order to compare the performance improvements that can be obtained for various turbidities and laser modulation frequencies. The work showed significant promise was published and presented this year (FY13) at the Oceans 2012 conference and additional theoretical and simulation work was performed to better quantify optimal delay requirements as a function of turbidity. Specifically, improvements on the order of 7 and 11 attenuation lengths are predicted through simulation when spatial filtering is applied to CW and dual-tone ranging, respectively. Application of the technique to experimental data showed only modest results; however, the experimental data did not include ranges that were long enough to test the algorithm. Dr. Linda Mullen's group at NAVAIR has performed additional experiments to validate the technique and they have prepared a manuscript for submission to the SPIE Oceans Optics which includes additional experimental results.

This year (FY13) a new ranging approach using a combination of frequency-domain reflectometry (FDR) and blind signal separation (BSS) has been developed that allows for automatic target detection at long unambiguous ranges. FDR was originally developed in the 1980s for the purpose of characterizing fiber lasers and approximating the location of faults in long fiber optic cables. This method has been shown to simultaneously achieve high range precision and long unambiguous ranging. The technique was simulated as a function of water turbidity using Rangefinder. In BSS, data are transformed into a statistical domain in which signals are separated based on their statistical properties. This technique is used to discriminate between the target return and backscatter. Used in conjunction with the FDR technique the blind signal separation was shown to provide an order of magnitude (x10) reduction in backscatter using Rangefinder simulation resulting in an automatic target detection improvement of 14 attenuation lengths. Experiments are underway to validate the new ranging algorithm and to better understand the tradeoffs associated with dwell time and shot noise limited performance. In summary, all techniques developed under this program to date have shown significant performance improvement potential in simulations and in preliminary experiments. Additional experimental validation of the techniques will be a key focus area for the upcoming year.

Progress

Background

Hybrid lidar-radar ranging systems experience two main challenges from operating in the underwater channel that degrade system performance, as shown in Figure 1. The first of these is absorption, which occurs when a photon emitted from the laser is absorbed by water molecules or dissolved materials. Absorption causes the received signal level to decrease. The use of blue wavelengths in open ocean or green wavelengths in coastal ocean can be used to minimize absorption. The second challenge occurs due to scattering, in which photons are deflected out from the collimated laser beam after colliding with particles in the channel. Scattering degrades resolution and reduces range accuracy. In addition, if a sufficiently large amount of photons scattered back into the receiver field of view, this can cause the system to erroneously detect an "object" at the center of the scattering distribution rather than detecting the desired target. Scattering has typically been mitigated by applying high modulation frequencies to the laser as backscatter has been shown to have a lowpass frequency response [1,2]. In terms of backscatter reduction, ***this work will focus on the application of digital signal processing algorithms to improve performance by processing the received signal rather than depending solely on the physics of the underwater channel.***

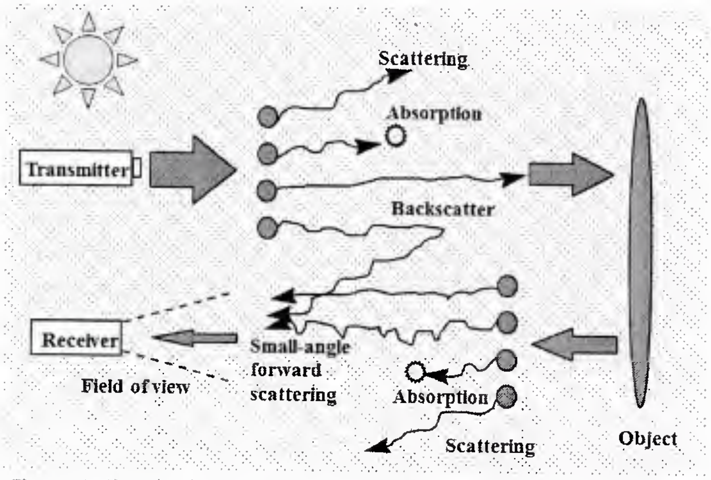


Figure 1. Sketch of water channel effects on hybrid lidar radar system

Although absorption and scattering are two separate physical phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c, which has units of m^{-1}. Beam attenuation in water follows an exponential decay law

$$P(c,z) = P_0 e^{-cz}$$

where z is the distance to the object and P_0 is the transmitted signal power. The product cz in the exponent is referred to as the number of attenuation lengths (a.l.), which is a dimensionless parameter used to compare ranging performance in different water conditions and at different distances.

Current Ranging Approaches

This section will briefly discuss two previous ranging approaches developed by Laux et al. [3] that were evaluated in the beginning of this work and serve as a baseline for our work. These approaches both work by modulating the laser and measuring the phase shift between the transmitted and received signals to compute the range. In the single modulation frequency continuous wave hybrid lidar-radar approach (CW), the laser is modulated with a single frequency. As a result, the performance of this method is defined by the wavelength of this modulation frequency.

This results in a number of tradeoffs, which are summarized in Table 1. CW ranging cannot simultaneously achieve high unambiguous range and high range precision. Additionally, there is a tradeoff between unambiguous range and backscatter suppression.

Table 1. Tradeoffs for single frequency CW method

Modulation frequency	Unambiguous range	Range precision	Backscatter suppression
Low	High	Low	Low
High	Low	High	High

The tradeoffs with the single frequency CW approach motivated the Navy to develop the dual frequency approach, in which the ranging performance depends on the difference between the two modulation frequencies. This allows the dual frequency approach to be operated with two modulation frequencies high enough to be above the backscatter cutoff point. This method still has performance tradeoffs to be concerned with, which are summarized in Table 2. As with the single frequency CW approach, there is a tradeoff between high unambiguous range and high range precision.

Table 2. Tradeoffs for dual frequency method

Difference frequency	Unambiguous range	Range precision	Backscatter suppression
Low	High	Low	High
High	Low	High	High

The CW and dual frequency ranging techniques will serve as a baseline for new signal processing techniques that have been developed under this program.

Spatial Filters for Backscatter Reduction

As previously mentioned, backscatter reduction is a critical stage in enhancing the usable range of any hybrid lidar-radar scheme that is deployed into a turbid underwater environment. In a highly scattering environment, many photons reaching the detector will have scattered off particulates in the water, while relatively few photons reaching the detector will have made the round-trip to and from the object of interest. This will cause the system to detect an object whose range is near the volumetric center of the scattering region, rather than the detecting the range to the object of interest.

Related challenges are encountered in moving target indication (MTI) radar and through-the-wall radar imaging (TWRI) radar, in which radar clutter obscures the desired object return [4,5]. TWRI researchers have shown that the clutter has lower spatial frequencies than the object, meaning that the clutter return can theoretically be filtered out by a spatial filter without negatively impacting the target return. The backscatter in the turbid underwater environment is analogous to the clutter in the TWRI radar scenario. An early solution to this problem was the use of delay line cancelers, with more recent work focusing on more sophisticated signal processing solutions such as FFT-based filters. The main idea behind the delay line canceler is that the clutter signal is a low frequency signal, which can be attenuated by a high-pass differentiator. Further modifications can be made to delay line cancelers to fine-tune the behavior, such as widening the clutter rejection region.

For proof-of-concept purposes, we have applied the simplest delay line canceler to the turbid underwater environment. This filter is a simple differentiator which rejects the DC component of the return signal, which is assumed in our case to correspond to the scattering contribution of the return signal. The filter is sketched in Figure 2, where Δz is the specified spatial delay. When this filter is applied to a turbid underwater environment, the attenuation of such an environment must be taken into consideration.

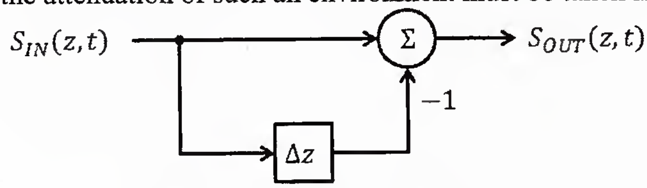


Figure 2. Single delay line canceler

The magnitude and phase responses for this filter are plotted in Figure 3 and Figure 4, respectively, for selected values of the attenuation coefficient c. The horizontal axis is shown as a factor of the transmitted signal's wavelength λ. Note that for the extreme case $c = 0$, the filter response reduces to the classical single delay line filter known in the radar community, which is periodic with period λ and suggests an optimal delay of $\Delta z_{opt} = \frac{\lambda}{2}$, in the sense that this is the first point at which point the signal magnitude is most amplified. On the other extreme, as c becomes large, the filter converges towards a high-pass filter with a relatively flat passband region. Additionally, as c increases, the optimal delay is shifting below $\frac{\lambda}{2}$ while the gain at this optimal point is decreasing from the gain in the $c = 0$ case. The optimal delay for selected values of c is summarized in Table 3, along with the magnitude gain and phase shift at these delay points. It is important to emphasize that the filter response depends on both the spatial delay Δz and the attenuation coefficient c. For example, if the turbidity increases, the filter response will change even when the spatial delay Δz is held constant. This implies that in a practical system the filter would need to be tunable to obtain optimal performance in different turbidities.

Since the spatial filtering approach operates on spatial frequencies rather than the electrical modulation frequency, this causes some potential drawbacks to this method. For a system that only has one photodetector, the platform must somehow be able to track the distance that it has traveled between measurements in order to apply the spatial filter. For systems above water or at shallow depth in calm waters, perhaps this could be achieved with high precision GPS. For systems in areas with strong currents, it would be very unlikely that the system could move an exact distance between measurements without potentially substantial deviations caused by the system drifting in the water. For systems in deep waters, the system will not be able to receiver GPS due to the attenuation of the GPS signal by the water. A submerged platform with two photodetectors at an appropriate spacing avoids this issue but introduces new challenges, primarily that the system size may increase significantly depending on the selected modulation frequency and corresponding optimal delay. Additionally, a system with two photodetectors should ideally place the detectors on an adjustable track so that the system could adapt the detector spacing to changes in modulation frequency or water conditions.

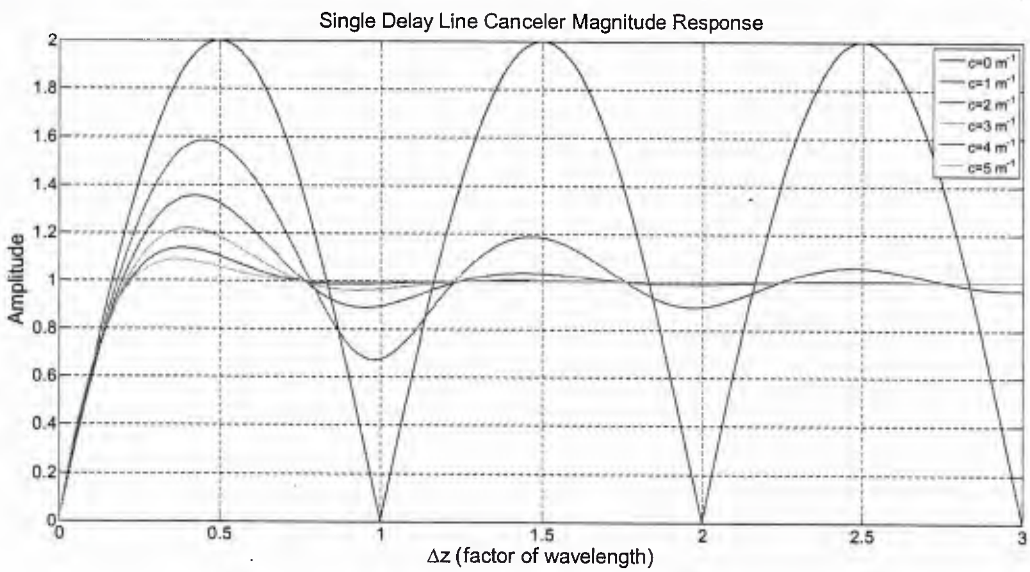


Figure 3. Magnitude response of single delay line canceler

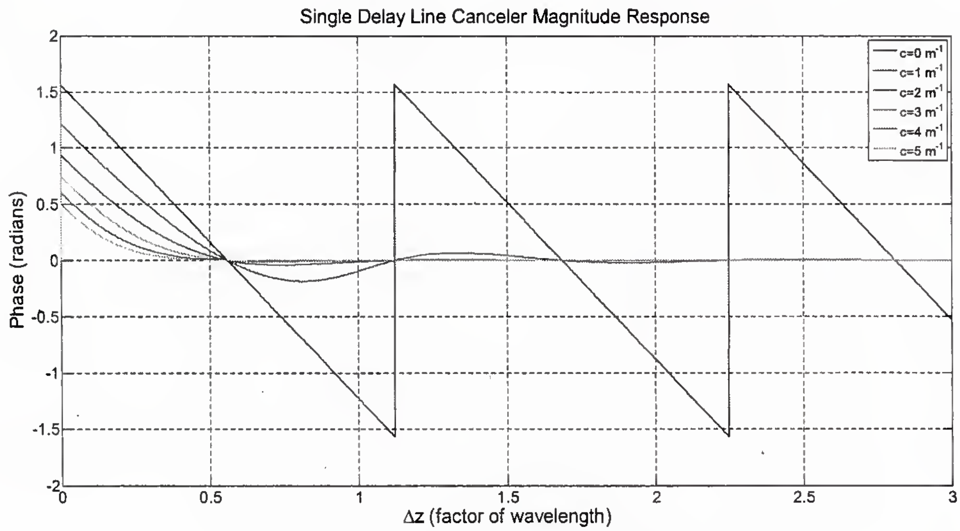


Figure 4. Phase response of single delay line canceler

Table 3. Optimal delays for selected attenuation coefficients

$c\,(m^{-1})$	0	1	2	3	4	5
Δz_{opt}	$0.500 * \lambda$	$0.455 * \lambda$	$0.425 * \lambda$	$0.402 * \lambda$	$0.385 * \lambda$	$0.371 * \lambda$
$M(\Delta z_{opt}, c)$	2.0	1.58	1.35	1.22	1.14	1.09
$\Phi(\Delta z_{opt}, c)$	10.00°	9.74°	6.40°	3.79°	2.15°	1.21°

Results

The spatial filter approach was applied to experimental data collected in 2012 by Dr. Linda Mullen's research group at Patuxent River Naval Air Station. Experimental results for the single frequency approach are shown in Figure 5, while the dual frequency approach results are shown in Figure 6. Both datasets were collected at a high turbidity of $c = 2.5\ m^{-1}$. The experiment was not originally designed to test the spatial filtering method, thus the data were not recorded at an appropriate interval for the optimal filter to be applied. Additionally, the data were heavily averaged prior to applying the spatial filter, which seems to have substantially reduced the impact that the spatial filter may have provided. The filter was observed to slightly reduce the ranging error at longer object distances. Additional experiments are planned to specifically evaluate the performance of the spatial filtering technique at longer ranges where the technique is expected to have the most benefit.

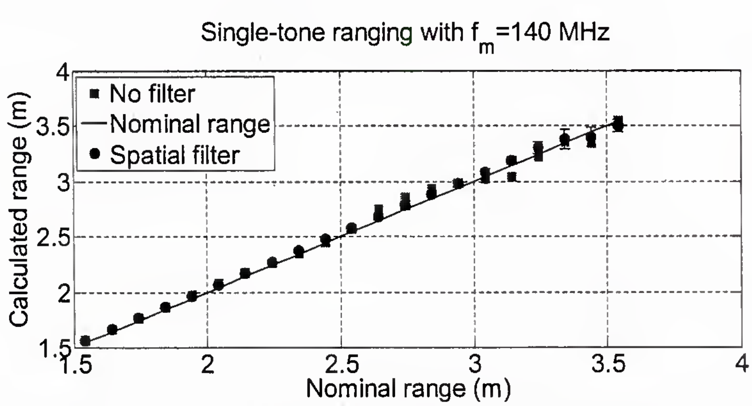


Figure 5. Experimental results for single frequency CW with spatial filter

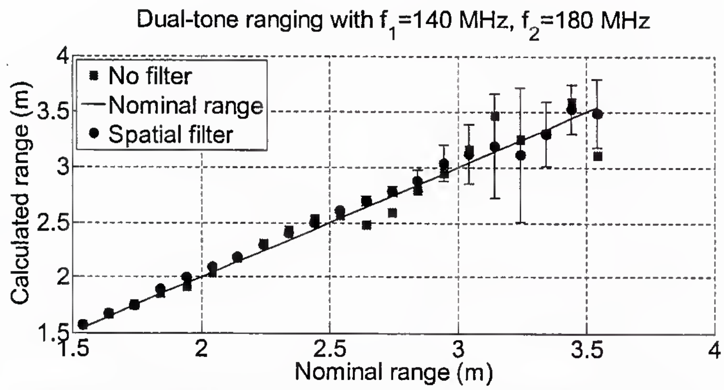


Figure 6. Experimental results for dual frequency CW with spatial filter

Due to the limited range of experimental data set, a set of simulations were run to assess the maximum extent to which each algorithm could range with and without the spatial filter. For the single frequency approach, the spatial filter extended the ranging ability from approximately 7 a.l. to a maximum of 9 a.l., as shown in Figure 7. The dual frequency simulation is shown in Figure 8, where the spatial filter improved the ranging performance by 11.5 a.l. to a maximum of 14.5 a.l. In both Figure 7 and Figure 8, the ranging algorithms begin to provide erroneous range values as they become scatter-limited. These simulations, while extremely promising, do not take into account shot noise limited scenarios and thus represent a best case scenario.

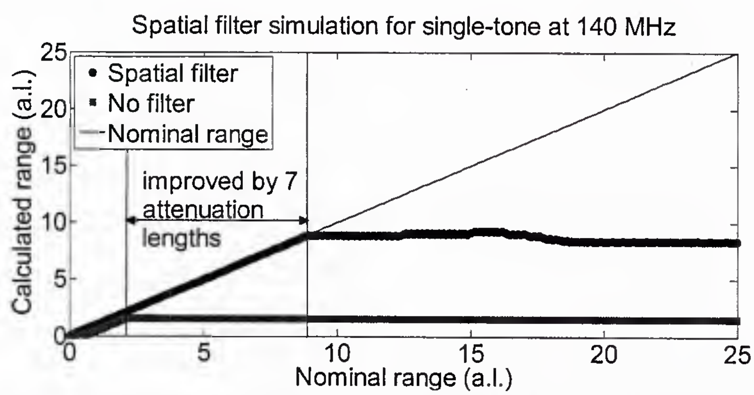


Figure 7. Simulation of theoretical limit on single frequency CW with spatial filter

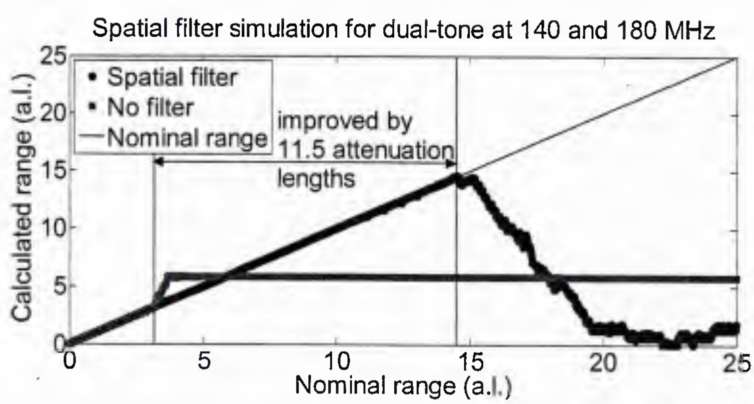


Figure 8. Simulation of theoretical limit on dual frequency CW with spatial filter

FDR – A New LIDAR Ranging Approach

In an attempt overcome the unambiguous range and range precision tradeoffs described previously, we have adapted a technique from the fiber optic community known as frequency-domain reflectometry (FDR). This technique was originally developed in the 1980s for the purpose of characterizing fiber lasers [6,7]. In the decades since, FDR has seen extensive use as an inexpensive method of approximating the location of faults in long fiber optic cables [8-11]. Utilizing modulation bandwidths of several gigahertz, this method has been used by the fiber optics community to unambiguously range over several kilometers of fiber optic cable with range resolutions on the order of 10 to 20 centimeters. Thus this method has been shown to simultaneously achieve high precision and high unambiguous ranging.

The key steps behind the FDR method will be briefly discussed. First, a stepped-frequency signal is transmitted into the channel. This signal reflects off objects in the channel and is collected by the receiver. The receiver measures the magnitude and phase of this return signal for all transmitted frequencies. This information is used to construct the frequency spectra for the current state of the channel, which encodes information about the distance to any objects currently in the receiver's field of view in the form of complex sinusoids. The inverse Fourier transform is taken to convert these complex sinusoids into sharp peaks in the time domain, indicating the time-of-flight required for the signal to reach each object in the channel. Finally, the time-of-flight information is converted into range data through knowledge of the speed of light in the medium.

Simulated results for a specific configuration of the FDR method are shown below in Figure 9. In this simulation, the target position was fixed at 5 meters to preserve system geometry, while the turbidity was varied such that the number of attenuation lengths was increased. The FDR configuration used a bandwidth of 1.2 GHz achieving a precision of 4.69 cm, with a step size of 1.17 MHz yielding an unambiguous range of 48 m. As seen in Figure 9, the measured range is within the specified precision until the target is 13 a.l. away from the system. This seemingly abrupt breakdown is actually a result of a steadily decreasing target to backscatter ratio, which is shown in Figure 10. This indicates that the FDR algorithm is able to provide performance to 13 a.l. corresponding to target-to-backscatter ratios of -2 dB without the use of any backscatter suppression algorithm.

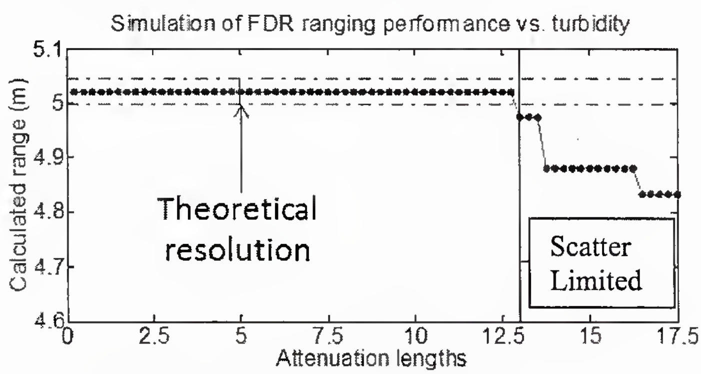


Figure 9. FDR performance vs. turbidity

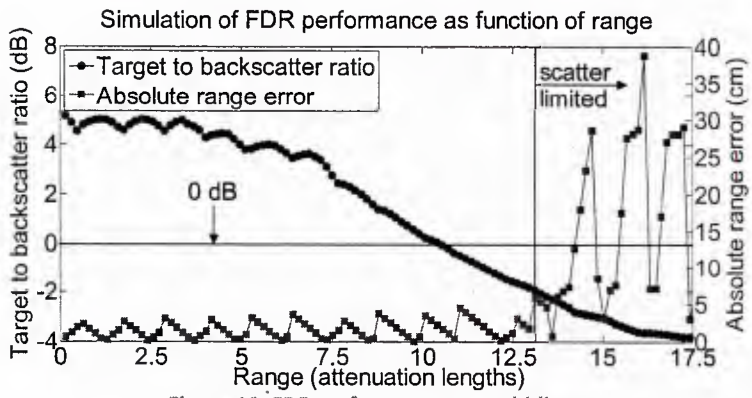


Figure 10. FDR performance vs. turbidity

Blind Signal Separation

For the FDR ranging approach, the statistical signal processing technique of blind signal separation (BSS) was adapted for backscatter reduction. In this technique, data are transformed into a statistical domain in which signals are separated based on their statistical properties [12]. This is analogous to using the Fourier transform to transform data into the frequency domain and separate signals based on their frequency content. Unlike the spatial filtering approach, BSS does not need to be adjusted for every modulation frequency, which made it a much more practical approach for backscatter suppression for the multiple frequencies required in the FDR method. A schematic of the BSS approach is shown below in Figure 11. In the top left, the frequency signal measured by FDR is shown, which contains both backscatter and target information. When this frequency signal is converted to range data, peaks for both the distributed backscatter and the target (correct location indicated with vertical green line) are obtained as shown in the top right. When BSS is applied to the frequency data, the scenario shown in the bottom left occurs, where the backscatter and target signals have been separated. By "zeroing out" the backscatter component, the range plot of the bottom right can be obtained, where the target still shows up in the correct position but the backscatter peak has been reduced by almost 10 dB. The BSS processing steps are critical in developing an automated target detection algorithm, such that the algorithm only detects a single peak instead of being confused by the backscatter return.

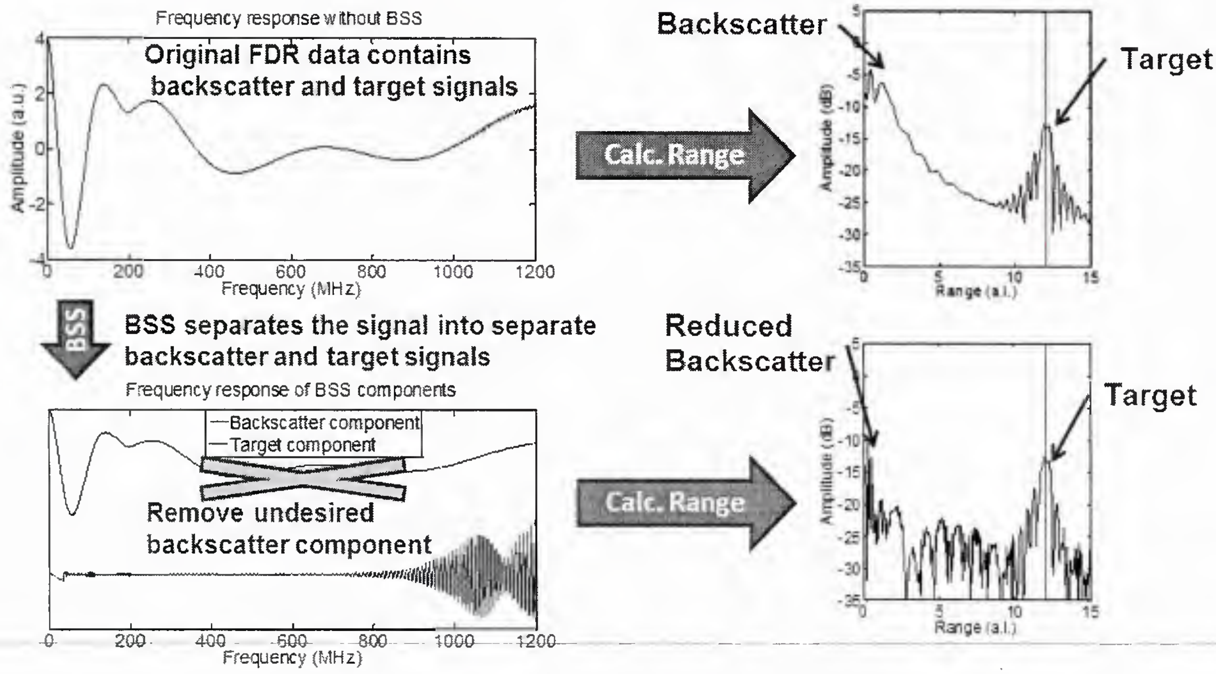


Figure 11. Schematic demonstrating approach for FDR with BSS

Simulated results for automatic peak detection

For proof-of-concept purposes, the automatic target detection is performed by a derivative-based method in which a search for a zero-crossing is performed. More advanced methods such as a correlation-based approach may be used in the future. Simulated results for this automatic peak detection approach are shown below in Figure 12 for the same configuration that was described previously: 1.2 GHz bandwidth yielding 48 m unambiguous range and 1.17 MHz step size yielding 4.69 cm precision. Without the BSS process to filter out the backscatter, the algorithm is able to range to 13 a.l. When BSS is applied, the algorithm is able to range to approximately 23 a.l., for an improvement of 10 a.l. This result is also 14 a.l. better than the single frequency CW approach with spatial filter, and 8.5 a.l. better than the dual frequency CW with spatial filter. As previously noted, these simulated results do not take into account shot noise limited performance. Nevertheless, the potential improvements are significant. Another practical aspect of the BSS algorithm that will be studied in the future are associated with the necessary dwell time required by the multi-tone approach.

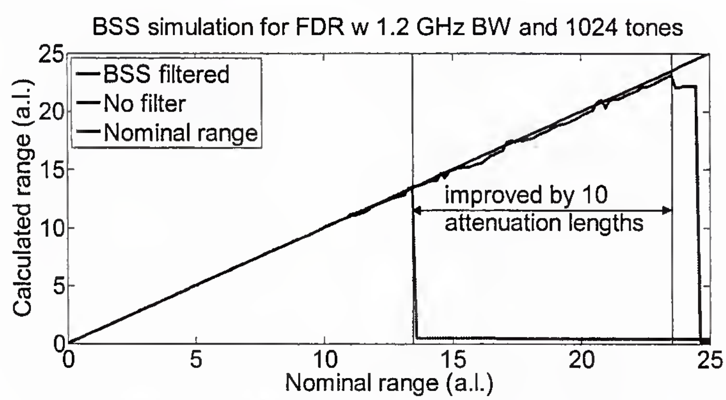


Figure 12. Ranging simulation for FDR with BSS filter

Planned work

The majority of the work planned for the immediate future rests upon experimentally verifying the FDR and BSS techniques under a variety of turbidities and practical system configurations which take into account shot noise limited performance. A secondary work objective is to determine how to optimize the necessary processing steps of the new ranging algorithm for use on real-time digital signal processing hardware. In addition, the FDR method will be assessed for possible additional applications due to the instantaneous channel response information that it provides.

Summary of new ranging approach

The new ranging approach developed aims to perform automatic target detection without requiring input from a human operator. In order to achieve unambiguous range and high range precision, the approach requires a wide bandwidth. The dwell time associated with this multi-tone technique also requires additional study. To summarize the major processing steps:

- Frequency-domain reflectometry allows a high unambiguous range measurement of the composite target and backscatter return
- Blind signal separation performs a statistical separation to extract the target return from the composite return signal by essentially filtering out the backscatter return
- Inverse Fourier Transform converts the filtered return signal into an instantaneous range spectrum
- Peak detection detects the range to the target

In scenarios where the FDR sweep is unable to achieve the desired precision due to bandwidth limitations, an optional fifth step can be performed in which a single modulation frequency CW approach may be used to obtain finer precision ranging information following the peak detection step.

Summary

Additional work has been performed to advance the spatial filter work started last year. Improvements on the order of 7 and 11 attenuation lengths are predicted through simulation when spatial filtering is applied to CW and dual-tone ranging, respectively. Application to experimental data showed only modest results; however, the experimental data did not include ranges that were long enough to test the algorithm. The Navy has performed additional experiments to validate the technique.

A new range approach using a combination of frequency-domain reflectometry (FDR) and blind signal separation (BSS) has been developed that allows for automatic target detection at long unambiguous ranges. Frequency-domain reflectometry provides a large unambiguous range independently of the range precision specification. Blind signal separation reduces backscatter in a post-processing fashion without requiring physical modifications to existing systems. Simulations indicate that the new approach can provide a ranging improvement of up to 14 attenuation lengths compared to previous approaches. Experiments are underway to validate the new ranging algorithm and to better understand the tradeoffs associated with dwell time and shot noise limited performance.

References

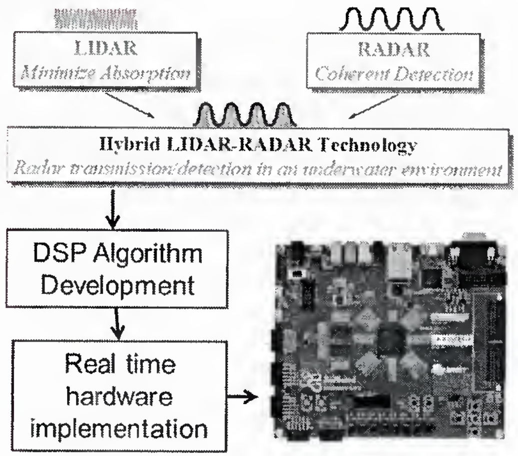
1. Mullen L.J., A.J.C. Vieira, and P.R. Herczfeld. "Application of RADAR technology to aerial LIDAR systems for enhancement of shallow underwater target detection," *IEEE Trans. Microw. Theory Techn.*, vol 43, pp. 2370-2377 (1995).
2. Pellen F., X. Intes, P. Olivard, Y. Guern, J. Cariou, and J. Lotrian. "Determine of sea-water cut-off frequency by backscattering transfer function measurement," *J. Phys. D: Appl. Phys*, vol. 33, pp. 349-354 (2000).
3. Laux, A., L. Mullen, P. Perez, and E. Zege. "Underwater Laser Range Finder," *Proceedings of SPIE 2012, Ocean Sensing and Monitoring IV*, vol. 8372 (2012).
4. Skolnik, Merrill I. *Introduction to Radar Systems*. 3rd ed. New York: McGraw-Hill, 2001.
5. Yoon, Y.-S., and M.G. Amin. "Spatial Filtering for Wall-Clutter Mitigation in Through-the-Wall Radar Imaging," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, no. 9, pp. 3192-3208, Sept. 2009.
6. MacDonald, R.I. "Frequency domain optical reflectometer," *Applied Optics*, vol. 20, no. 10, pp. 1840-1844, May 1981.
7. Eickhoff, W. and R. Ulrich. "Optical frequency domain reflectometry in single-mode fiber," *Applied Physics Letters*, vol. 39, no. 9, pp. 693-695, Nov. 1981.
8. Healey, P. "Review of Long Wavelength Single-Mode Optical Fiber Reflectometry Techniques," *Journal of Lightwave Technology*, vol. LT-3, no. 4, Aug. 1985.
9. Ghafoori-Shiraz, H. and T. Okoshi. "Fault Location in Optical Fibers Using Optical Frequency Domain Reflectometry," *Journal of Lightwave Technology*, vol. LT-4, no. 3, Mar. 1986.
10. Barfuss, H. and E. Brinkmeyer. "Modified Optical Frequency Domain Reflectometry with High Spatial Resolution for Components of Integrated Optic Systems," *Journal of Lightwave Technology*, vol. 7, no. 1, pp. 3-10, Jan. 1989.
11. Furse, C., Y.C. Chung, C. Lo, P. Pendayala. "A critical comparison of reflectometry methods for location of wiring faults," *Smart Structures and Systems*, vol. 2, no. 1, pp. 25-46, 2006.
12. A. Hyvärinen and E. Oja. "Independent component analysis: algorithms and applications," Neural Networks, vol. 13, no. 4/5, pp. 411-430 (2000).

Clarkson UNIVERSITY defy convention

Advanced Digital Signal Processing for Hybrid Lidar N000141110371

Objective:

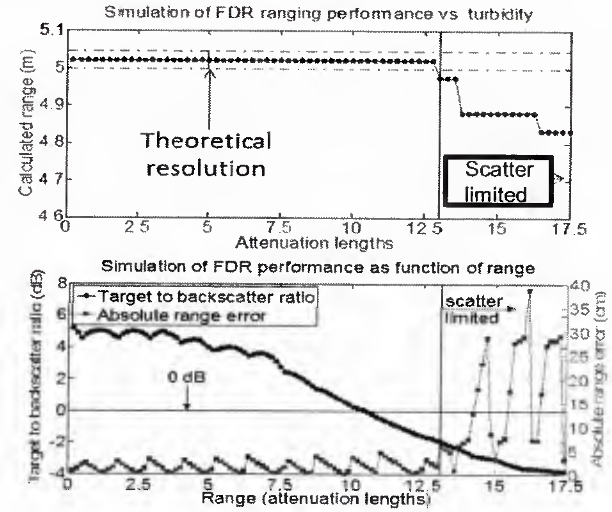
- Develop and evaluate various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance.



Approach:

- Account for both practical hardware implementation and realistic underwater propagation characteristics
- Leverage existing Navy proximity detection work
- Use a combination of simulated and experimental lidar data to validate algorithms
- Leverage mature signal processing techniques developed for radar and communications to the maximum extent possible

Figure: A new ranging and backscatter reduction technique have shown that backscatter can be reduced by 10dB and that the correct range can be automatically detected.



Scientific or Naval Impact/ Results:

- Potential performance improvements predicted by simulation are significant
- Validate with more experimentation this year
- Address several practical system issues this year

Ranging Algorithm	Backscatter Reduction Algorithm	Automated Detection Algorithm	Results Achieved via Rangefinder Simulation
Continuous Wave (CW)	Spatial Filter	N/A	Range detection improved by 7 attenuation lengths
Dual Frequency	Spatial Filter	N/A	Range detection improved by 11.5 attenuation lengths
Frequency Domain Reflectometry (FDR)	Blind Signal Separation (BSS)	Peak detection	Backscatter reduced by 10dB and range detection improved over CW by 21 attenuation lengths